AD-A020 932

DARPA-NRL INTEGRATED OPTICS PROGRAM QUARTERLY TECHNICAL REPORT TO DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

William K. Burns, et al

Naval Research Laboratory

Prepared for:

Defense Advanced Research Projects Agency

December 1975

NRL Memorandum Report 3185

DARPA-NRL Integrated Optics Program
Quarterly Technical Report to Defense Advanced Research Projects Agency January 1, 1975 – August 1, 1975

WILLIAM K. BURNS AND THOMAS G. GIALLORENZI

Optical Physics Research Group
Optical Sciences Division

December 1975

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER NRL Memorandum Report 3185	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DARPA-NRL INTEGRATED OPTICS PROGRAM — Quarterly Technical Report to Defense Advanced Research Projects Agency — January 1, 1975 - August 1, 1975		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem. 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) William K. Burns and Thomas G. Giallorenzi		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem N01-38 DARPA Order 2327
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency Washington, D.C. 22209		12. REPORT DATE December 1975 13. NUMBER OF PAGES 16
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Integrated optics
Branching waveguides
Optical waveguides
Indiffused $LiNbO_3$ waveguides

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The ARPA-NRL Integrated Optics program is concerned with the development of infrared integrated optics technology and with the development of a single-mode optical data bus. This report summarizes the NRL in-house progress in the area of indiffused $LiNbO_3$ waveguides, separating waveguides for the data bus, and single-mode optical data bus planning. In particular, the results of a theoretical study of separating waveguides are presented.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

DARPA-NRL INTEGRATED OPTICS PROGRAM

QUARTERLY TECHNICAL REPORT

Reporting Period

1 January 1975 - 1 August 1975

1.	ARPA Order	2327
2.	Program Code Number	3D10
3.	Name of Contractor	Naval Research Laboratory Optical Sciences Division
4.	Effective Date of Contract	1 July 1974
5.	Contract Expiration Date	Continuing
6.	Amount of Contract	$110K
7.	Contract Number	N/A
8.	Principal Investigator	Dr. T. G. Giallorenzi
9.	Phone Number	(202) 767-3209
10.	Scientific Officer	Dr. C. M. Stickley
11.	Title of Work	A Coordinated Research Program to Develop Infrared Integrated Optics and Single Mode Optical Data Transfer Links.

Sponsored by

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
DARPA Order NO. 2327

Note: Manuscript submitted November 25, 1975.

TECHNICAL SUMMARY

TECHNICAL STATUS

This report summarizes the results of two journal papers recently submitted for publication by NRL on modal evolution 3-dB couplers[1] and on modes in diffused optical waveguides.[2]

OBJECTIVES

The main aim of this study is to develop and characterize an electro-optic branching waveguide switch in a $LiNbO_3$ optical waveguide system. Such a switch could be devised in several ways: as a single electro-optically controlled branch, or by two 3-dB couplers connected by an active phase shifter in one arm (Mach Zehnder interferometer). Also operation with planar waveguides or three-dimensional channel waveguides could be considered.

MODAL EVOLUTION 3-dB COUPLER

A. Theory

The possible advantages associated with achieving electro-optic switching by the use of the Mach Zehnder interferometric technique led us to investigate a new type of 3-dB coupler (50-50 power divider) which is an essential component to the complete switch. The coupler which we proposed and have demonstrated is based on the principles of mode conversion and modal evolution, rather than the conventional mode interference directional couplers, and allowed us to build on theories previously developed describing mode conversion in separating waveguides[3] and tapered velocity couplers.[4] We have been able to extend the theoretical concepts developed to describe our planar modal evolution 3-dB coupler to the description of conventional directional 3-dB couplers and branching modal evolution 3-dB couplers similar to those recently reported experimentally by Martin.[5]

In Fig. 1a is shown a cross-section of the planar modal evolution 3-dB coupler. The coupler consists of two coupled waveguides, made synchronous by a small section of overlaid superstrate. The overlay is introduced abruptly and removed slowly by constructing it with fast and slow tapers. Operation of the device is illustrated by the electric field amplitudes of the local normal modes i and j shown at 3 positions along the propagation direction z.

An input mode i, from the left, undergoes mode conversion at the fast taper and transfers half its power to normal mode j. At this point each mode has power in both guides 2 and 4, due to the mode synchronism shown in Fig. 1b. During adiabatic transfer through the slow taper, the modes evolve without power transfer such that each is primarily confined to a single guide, and 50-50 power division is achieved. The advantages of this type of device over a conventional

3-dB directional coupler are that synchronism is required only at the point $z = 0$ and the device length is non-critical.

We have used an approximate coupled mode representation of the coupling between local normal modes to estimate power transfer between normal modes at the abrupt transition. This result gave reasonable agreement with our experimental results. In order to characterize "fast" and "slow" tapers in terms of mode conversion, or power transfer between normal modes, we extended a previously developed technique[3,4] capable of identifying the parameter characteristic of mode conversion in a particular device, as well as estimating its midpoint value. The criteria for substantial mode conversion in a fast taper is

$$\frac{|K|}{\alpha_f \gamma_5} << .44 \ , \tag{1a}$$

whereas to avoid power transfer due to the slow taper we require

$$\frac{|K|}{\alpha_s \gamma_5} >> .44 \ . \tag{1b}$$

K is the coupling constant between the coupled guides, α_f and α_s are the slopes of the fast and slow tapers, and γ_5 is the transverse momentum in the overlay.

It has become apparent that the limiting case of a very steep (complete mode conversion) branching waveguide is equivalent to a 3-dB coupler, in that the incident power is divided equally into each branch. This also is apparent from symmetry considerations when the branch is synchronous by reason of geometrical symmetry. In fact, as we will discuss further in the next paragraph, branching waveguides can be used to construct a two dimensional analog of the planar modal evolution 3-dB coupler. Smith[6] has shown for the tapered velocity coupler that coupling efficiency has a simple exponential dependence on a parameter characteristic of that device. This result can also be interpreted in terms of mode conversion between local normal modes, and should be capable of extension to any modal evolution device. We do so in Fig. 2 where the equation

$$\text{Power Transfer} = \frac{1}{2} e^{-\pi y} \tag{2}$$

is fit to computer data for power transfer between local normal modes in separating or branching waveguides. This relationship should hold for both planar modal evolution 3-dB couplers, where $y = |K|/\alpha\gamma_5$, as well as for branching waveguides, where $y = \Delta\beta/\theta\gamma_3$. $\Delta\beta$ is the difference in propagation constant for large branch separation, θ is the taper slope, and γ_3 is the transverse propagation constant in the separating region. On this plot are also shown the positions corresponding to the slopes of the fast and slow tapers fabricated experimentally for the planar modal evolution 3-dB coupler. From the theory developed we see that nearly complete mode conversion was achieved at the fast taper, and zero mode conversion at the slow taper, as desired.

In the modal evolution 3-dB coupler, 3-dB worth of cumulative mode conversion between local normal modes is provided in a single abrupt transition. It is convenient to describe the device in terms of the parameter $X = \Delta\beta/2K$ where $\Delta\beta = \beta_x - \beta_z$ is the difference in guide propagation constants and K is the coupling constant. As shown in Fig. 1b, $|X|$ changes abruptly from a value much greater than unity to a value near zero, and then gradually increases again in order to spatially separate the local normal modes in an adiabatic fashion. In the planar device, this variation in $|X|$ was accomplished by changing $\Delta\beta$. A similar variation can be achieved by changing K, and this is the basis for the two dimensional modal evolution 3-dB coupler made with two branching waveguides. (Fig. 3a). In this arrangement the first branch acts as a power divider and provides 3-dB worth of cumulative mode conversion; the second branch acts as a mode splitter and provides adiabatic spatial separation of the local normal modes. The advantage of this device is that large swings in $|K|$ and therefore $|X|$ are conveniently available to the designer. The device shown in Fig. 3a is a generalization of the 3-dB coupler recently used by Martin to construct an interferometric switch.[5]

The conventional directional coupler is shown in Fig. 3b. It consists of two parallel waveguides in a central region of length L where adiabatic propagation occurs. Two abrupt transitions terminate the central adiabatic region and spatially separate the local normal modes. These two transitions can be either separating waveguides acting as power dividers, or with channel guides an overlay can be used to define the central region and provide the abrupt transitions. In either case normal mode interference occurs in the central region and precise knowledge of $|K|$ is needed to design L. This points out the advantage of the modal evolution 3-dB couplers of Figs. 1a and 3a. For these devices there is only a single region of mode conversion between local normal modes and no critical length L appears.

B. Experiment

The planar device was fabricated from sputtered layers of barium silicate glass (guiding) and fused silica (cladding). Fig. 4 outlines the fabrication steps involved with the overlay fast and slow tapers. The slow taper was achieved by masking during sputtering, whereas the fast taper was obtained by sputter etching with a photo-lithographically delineated mask. Details are provided in Ref. 1.

Fig. 5a shows a sketch of the completed structure. Propagation is in the z direction and the guiding layer 4 is tapered in the y direction in order to achieve mode synchronism somewhere in the middle of the sample. Experimental results of power transfer between the normal modes as a function of distance across the sample (y direction) are shown in Fig. 5b. The variation across the sample is due to the taper in layer 4 and is predicted by the theory developed for power transfer at an abrupt transition. Maximum power converted (40%) was limited by a problem with the sputter etching process in fabricating the abrupt step in the superstrate. Specifically the abrupt step did not have a fast slope over the whole step, but had a slower slope section (up to 30%) at the base of the transition. This resulted in the theoretical curve marked X_0 (actual), rather than that marked X_0 (design), which gives reasonable agreement with the experimental results.

MODES IN DIFFUSED OPTICAL WAVEGUIDES

In conjunction with G. B. Hocker, visiting NRL in the fall of 1974, we have carried out and published[(2)] a theoretical and experimental study of mode dispersion in planar diffused optical waveguides of arbitrary index profile. The primary result of this work was that universal curves that describe mode dispersion for waveguides with a specific diffusion profile could be obtained. Such curves for complementary error function and Gaussian diffusion profiles are shown in Fig. 6. These plots are normalized so that they characterize any diffused waveguide with that profile. The approximations made in producing the universal curves are very good for high index systems such as $LiNbO_3$. The same analysis also produced universal mode number charts which predict the number of modes that propagate in a diffused planar guide of specific diffusion profile for a given diffusion depth, D, and surface index change, Δn.

Also plotted in Fig. 6 are experimental measurements on two nickel diffused $LiNbO_3$ waveguides. The better fit of the data to the erfc dispersion curves indicates that the diffusion profiles obtained were nearly complementary error function. This illustrates how these universal curves can be used to indicate what diffusion profiles are experimentally obtained, without making direct measurements. Ti-diffused planar waveguides have been produced with losses of 1 dB/cm or better.

This work is presently being extended, theoretically and experimentally to two-dimensional channel waveguides.

MISCELLANEOUS

In addition to the work reported here, additional results on this program have been submitted to the Topical Meeting on Integrated Optics. These results, in the form of one invited and four contributed papers, will be included in subsequent DARPA reports. The titles of these papers are:

1. "Power Transfer Between Local Normal Modes in Dielectric Waveguides," by Drs. W. K. Burns and A. F. Milton (invited).

2. "Mode Dispersion in Diffused Channel Waveguides by the Equivalent Index Technique," by Drs. W. K. Burns and G. B. Hocker.

3. "Mode Liftoff Using a Branching Dielectric Waveguide," by Drs. H. P. Hsu and A. F. Milton.

4. "Performance Limitations Imposed on Integrated Optical Devices by Polarization," by Drs. R. Steinberg and T. G. Giallorenzi.

5. "The Design of Adiabatic Transitions for Integrated Optics," by Drs. A. F. Milton and A. J. Skalafuris.

<u>REFERENCES</u>

1. W. K. Burns, A. F. Milton, A. B. Lee, and E. J. West, to be published in Applied Optics.

2. G. B. Hocker and W. K. Burns, IEEE J. Quantum Electron. <u>QE-11</u>, 270 (1975).

3. W. K. Burns and A. F. Milton, IEEE J. Quantum Electron. <u>QE-11</u>, 32 (1975).

4. A. F. Milton and W. K. Burns, Applied Optics <u>14</u>, 1207 (1975).

5. W. E. Martin, Appl. Phys. Lett. <u>26</u>, 562 (1975).

6. R. B. Smith, submitted to Electronics Letters.

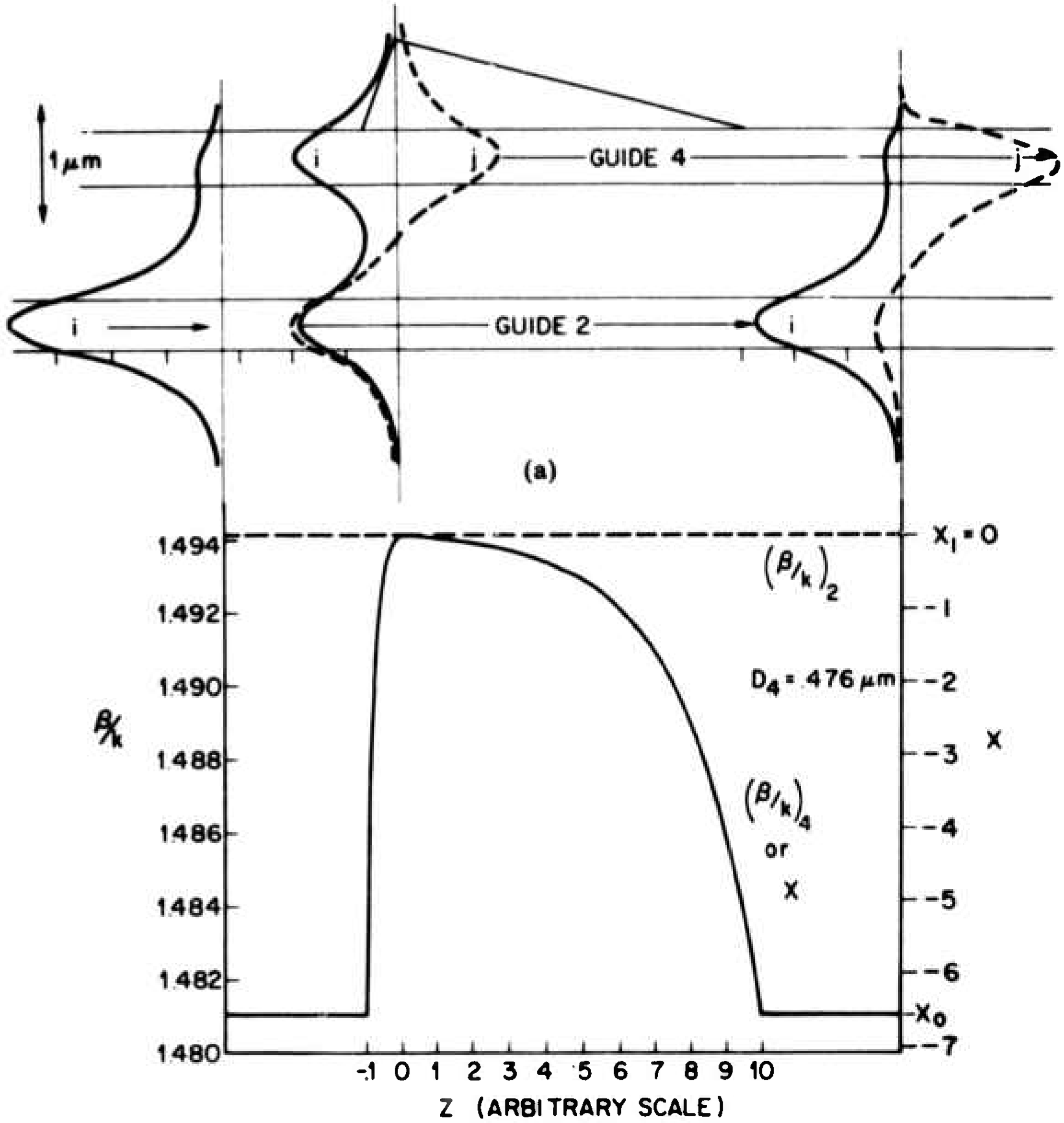


Fig. 1 — (a) a cross section of a planar modal evolution 3-dB coupler with the electric field amplitudes of the local normal modes i and j at three positions along the propagation direction a. The input mode i has unity power and 3-dB coupling is shown. In (b) the corresponding values of $X = \Delta\beta/2\,|K|$ and the uncoupled mode effective indices are shown. To the left of z = 0 the z scale is exaggerated to show the fast taper.

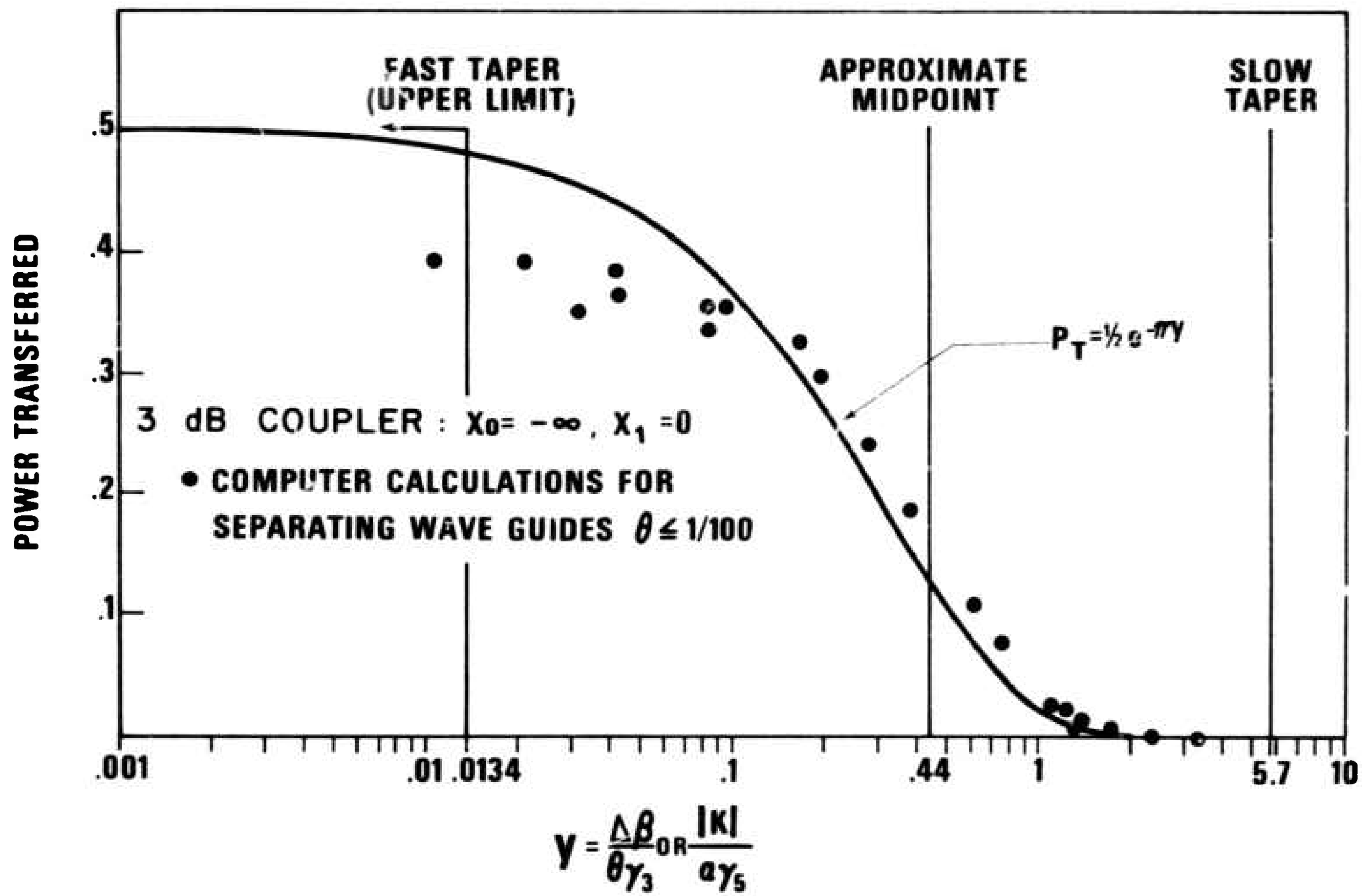
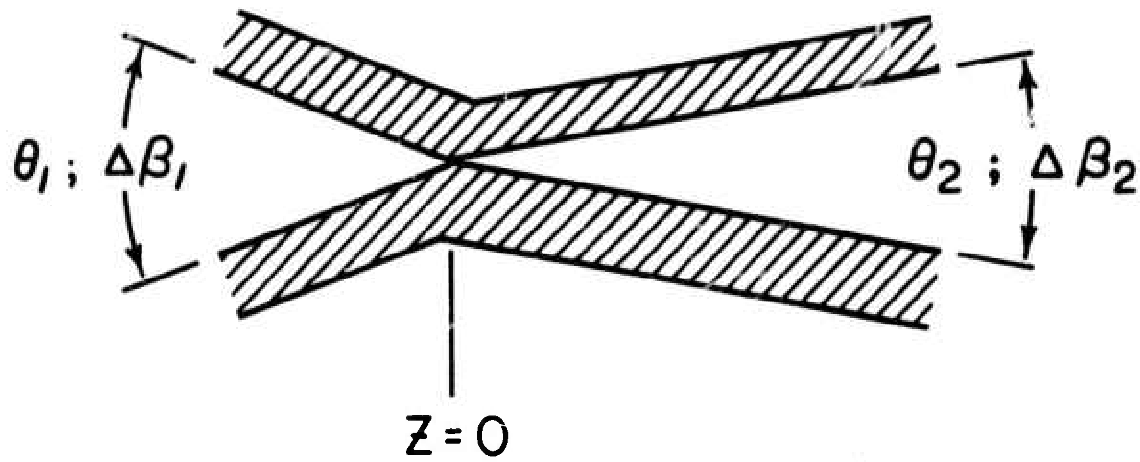
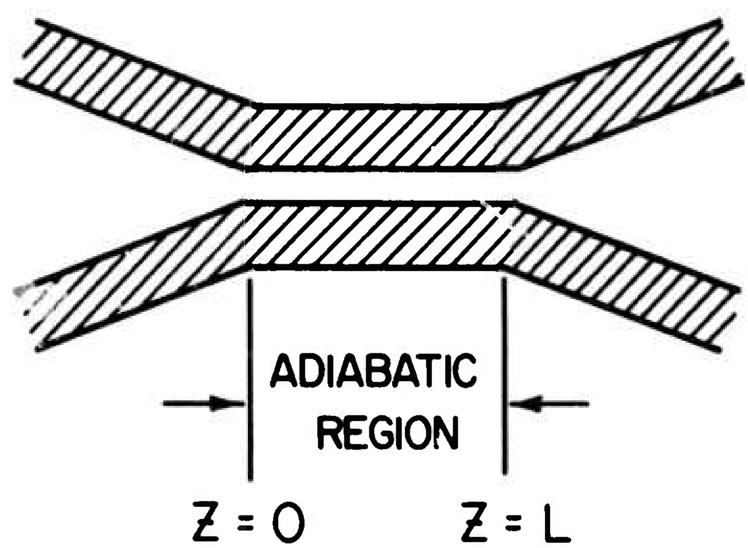


Fig. 2 — Power transferred between local normal modes in a modal evolution 3-dB coupler or a branching waveguide as a function of a parameter, y, characteristic of mode conversion in each device. The vertical lines locate the fast and slow tapers experimentally achieved in a planar 3-dB coupler. The points representing separating waveguides are taken from Ref. 3.



(a)



(b)

Fig. 3 — Sketches of a two-dimensional, channel modal evolution 3-dB coupler (a) and a conventional mode interference 3-dB coupler (b). In (a) a single region of mode conversion ($z < 0$) acts as a power divider, and is followed by a adiabatic region which acts as a mode splitter. In (b) two regions of mode conversion are separated by an adiabatic region of length L.

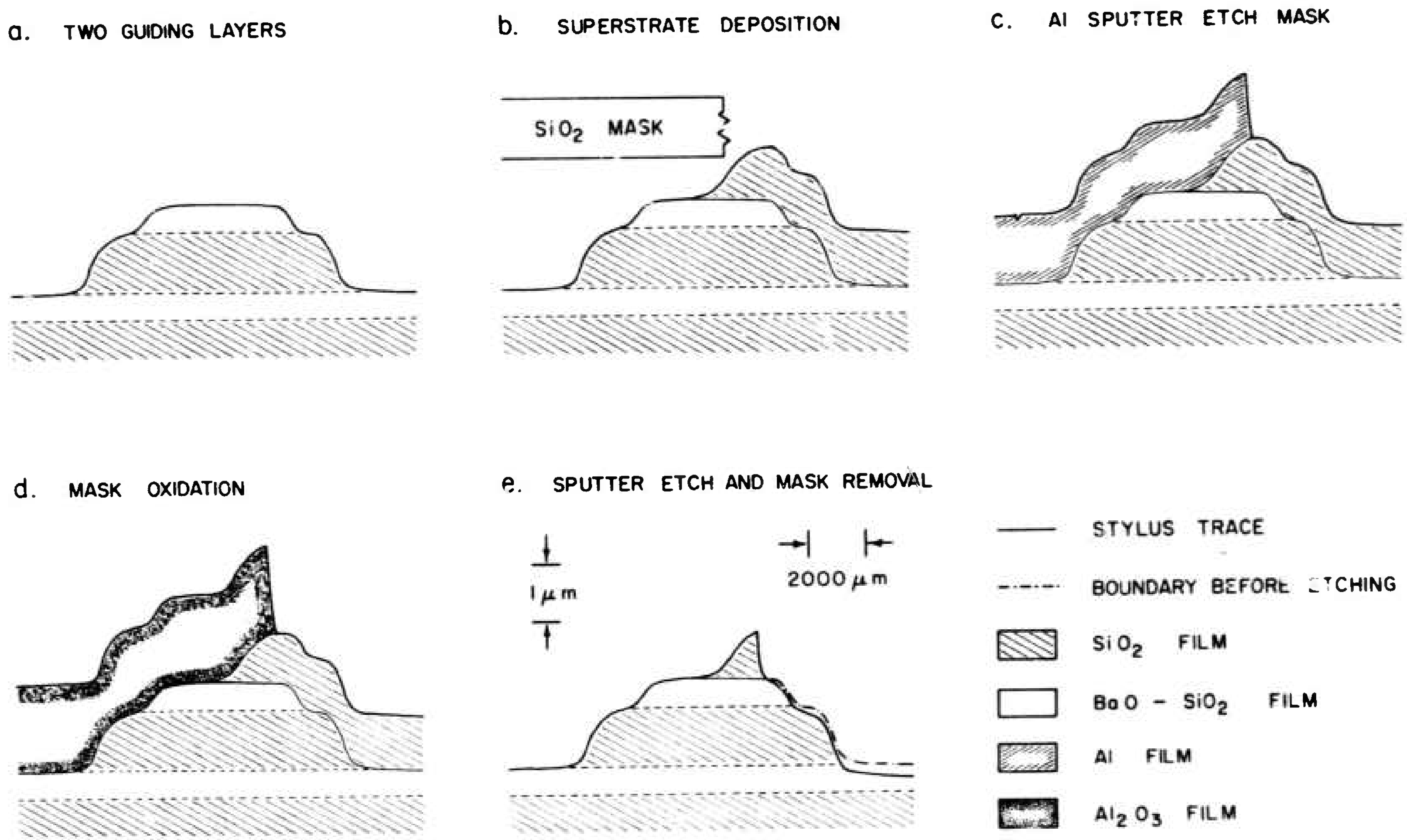


Fig. 4 — Mechanical stylus traces showing various fabrication steps of the planar 3-dB coupler. Each figure except (a) is reconstructed from two or more traces and may be in error due to slight differences in leveling for each trace.

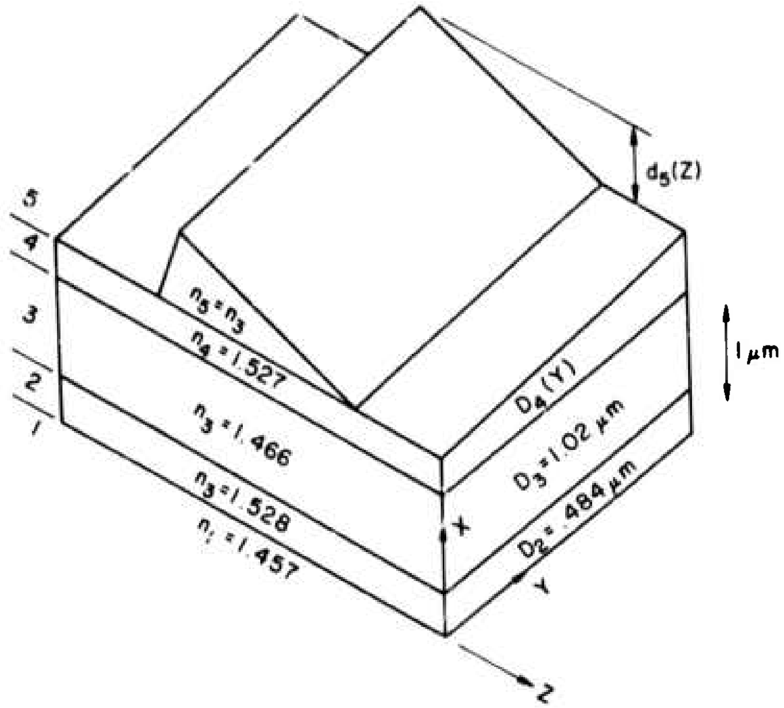


Fig. 5(a) — Sketch of the planar 3-dB coupler with experimentally measured film thicknesses and indices. Layer 4 has a thickness variation in the y direction. Propagation is in the z direction.

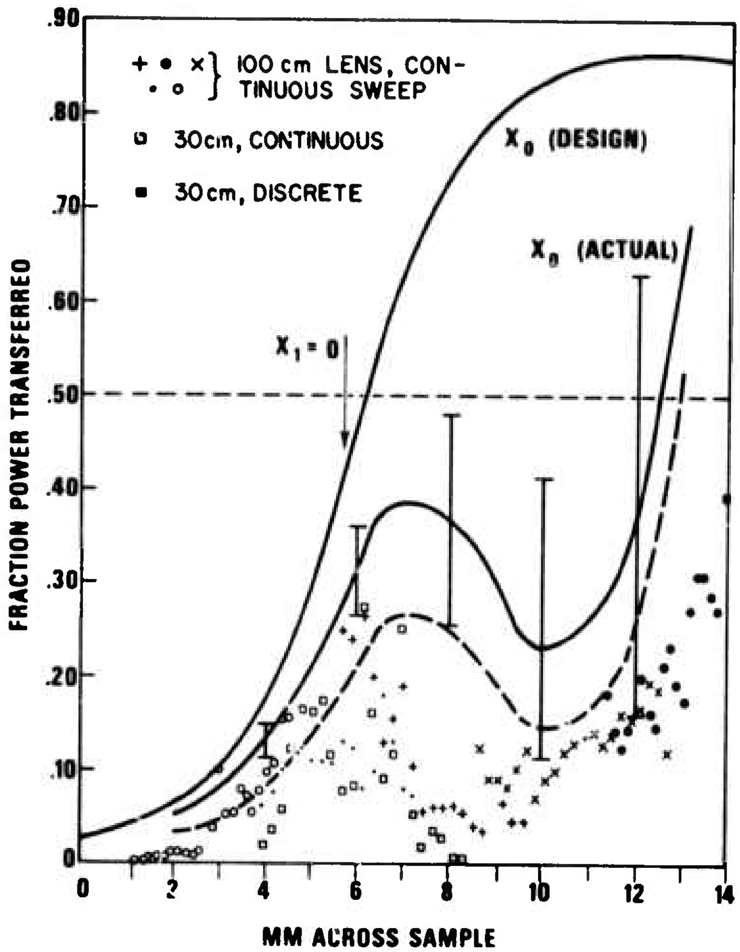
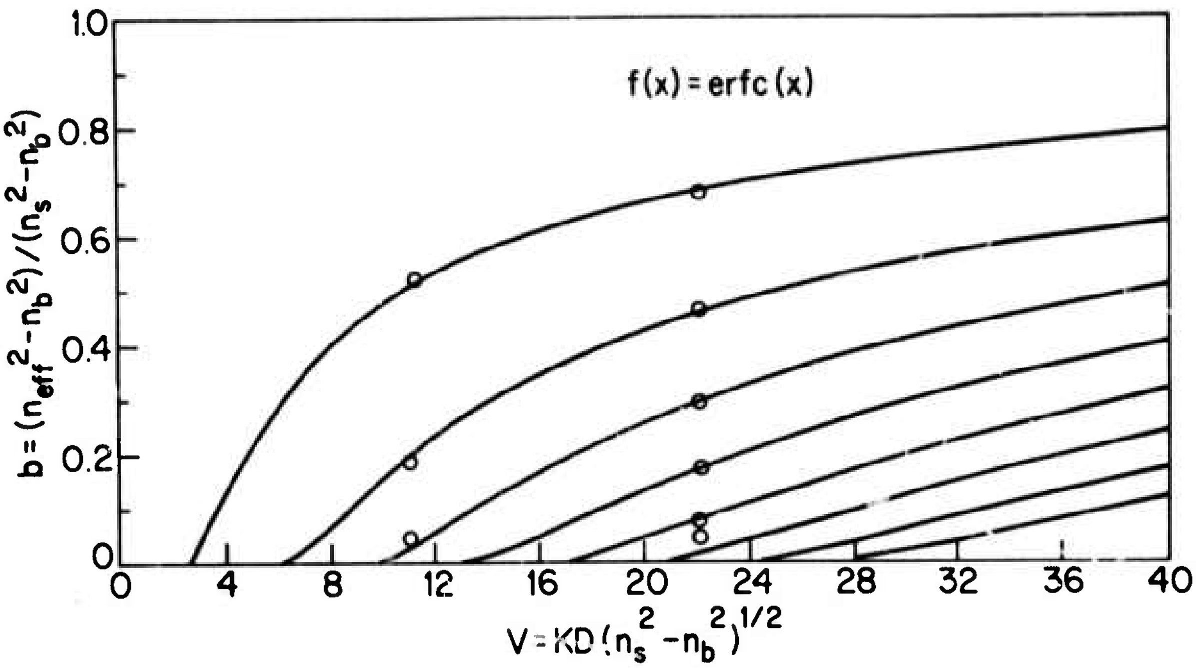


Fig. 5(b) — Experimental and theoretical results for power transfer between local normal modes in the planar 3-dB coupler as a function of position across the sample in the y direction. The curve X_0 (design) becomes that marked X_0 (actual) when the slow slope portion of the fast taper is accounted for. Inclusion of the differential losses between the coupled guides yields the dashed curve, which gives a reasonable fit to the experimental points.



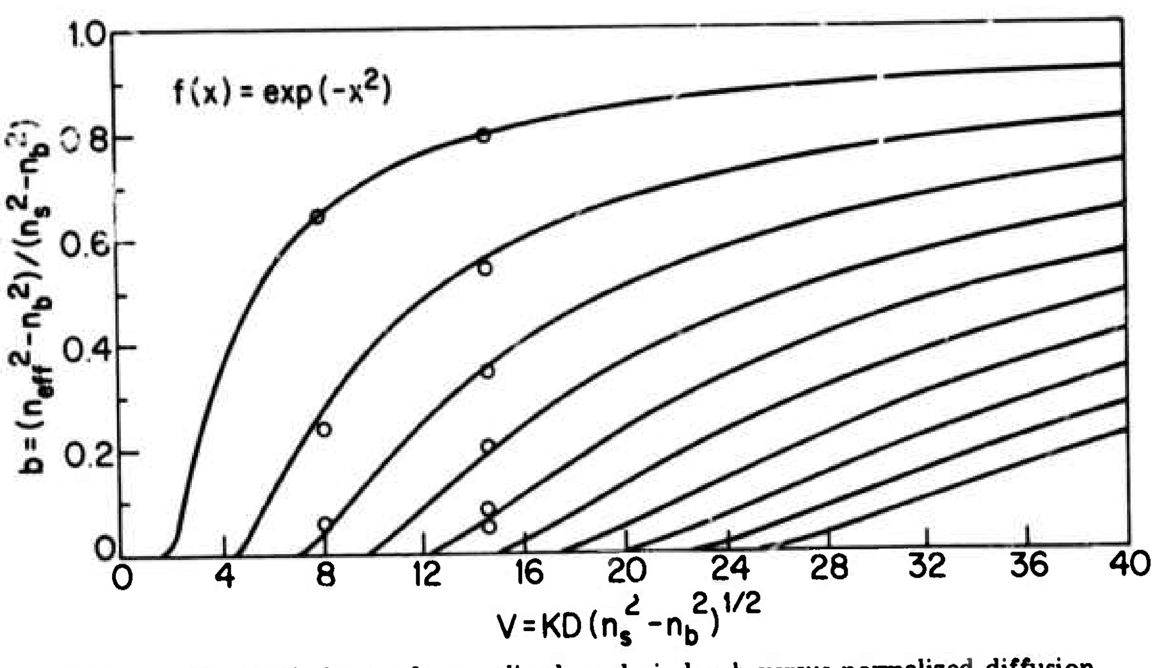


Fig. 6 — Universal charts of normalized mode index b versus normalized diffusion depth V for complementary error function and Gaussian diffusion profiles. Experimental measurements of TM mode effective indices in two Ni-diffused $LiNbO_3$ guides are fitted to the charts. More recent data has improved the fit to the erfc profile for the sixth mode of the six-mode guide.